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WT-1308

OPERATION REDWING—PROJECT 1.9b

INDIRECT WATER WAVES FROM LARGE-YIELD BURSTS (U)

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ABSTRACT

Long-period surface water waves produced by megaton-range shots at Bikini Atoll during Operations Castle and Redwing were recorded at Ailinginae, Eniwetok, Wake, Guam, and Johnston Islands. Analysis of the results indicate that the waves originated close to Bikini, and propagated outward as a train of solitary waves of slowly decreasing amplitude and period, as measured at a single station. In each case, the train was slightly dispersive for roughly the first 500 naut mi, with wave height decaying inversely with range. It remained essentially unchanged in form thereafter, with height diminishing as the inverse square root of the range. The character of the dispersion and the subsequent behavior of the trains are not predicted by current theory. As measured at any station, the observed wave height varied directly with the shot yield, instead of the square root, as expected from theory. This relation can be explained by shadowing effect of the atoll.

Curves for predicting deep-water wave heights at any range, as a function of yield and source geometry for surface shots over an atoll, are provided. The extension to other geometries is discussed.

FOREWORD

This report presents the results of one of the projects participating in the military-effect programs of Operation Redwing. Overall information about this and the other military-effect projects can be obtained from WT-1344, the "Summary Report of the Commander, Task Unit 3." This technical summary includes: (1) tables listing each detonation with its yield, type, environment, meteorological conditions, etc.; (2) maps showing shot locations; (3) discussions of results by programs; (4) summaries of objectives, procedures, results, etc., for all projects; and (5) a listing of project reports for the military-effect programs.

PREFACE

Previous thinking based on the results of water-wave studies conducted during Operations Ivy, Castle,[1] and Redwing, (Reference 1) concluded that the long-period gravity waves generated in deep water outside the lagoon by megaton-range explosions on or over atolls were produced by some unexplained type of air coupling from the integrated surface impulse at great distances from the shot site, hence their appellation, "indirect waves". More-detailed study reported herein, however, indicates that the hypothesis of remote generation is inconsistent with the correlation between wave arrival times and the known speed of propagation of long waves in deep water, the vanishingly small magnitude of air overpressures at great ranges, and theoretical models of wave generation from known impulse distribution.

As presently conceived, the waves outside the lagoon were generated by the fringe of the high-impulse region close to the shot site extending beyond the atoll rim.

[1]Permission to include previously unreported data from Castle in this document has been given by the Armed Forces Special Weapons Project.

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INDIRECT WATER WAVES FROM LARGE-YIELD BURSTS

OBJECTIVES

The program for the measurement of indirect waves under Project 1.9 was concerned with continuing the documentation of long-period waves produced by tests of devices in the megaton class initiated for Operation Ivy and carried out during Operation Castle. The objective of this study was to determine the capability of predicting in advance of future tests the nature and characteristics of the long-period waves known to be produced by such tests at ranges well outside the zone of significant blast damage. Such waves fall in the category of "tsunamis", or seismic sea waves (which are usually produced by submarine earthquakes and which suffer only gradual attenuation while traveling great distances). They are of military and civil importance because of the potential damage that might result from large weapons.

BACKGROUND

While it was presumed that the shots of Operation Redwing would not produce dangerous waves of a tsunami nature, they would still be large enough to study in detail at ranges over 1,000 miles. The qualitative results from Operation Castle indicated that the amount of energy going into making long waves increases as the square of the shot yield, and it is presumably possible at present to construct weapons capable of producing damage at these ranges.

Results prior to Redwing have shown that large weapons detonated in or over lagoon sites produce, at great distances outside the blast zone, waves having periods in the range from 5 to 8 minutes (wave length 30 to 50 miles) and having a height of a few inches. These waves travel with a velocity determined by the depth of water. In the Pacific Ocean, the velocity is about 400 knots. Upon reaching continental shorelines or islands large compared to their wave length, these waves undergo local intensification through the processes of refraction, peaking, funneling, and reflection. In addition, they produce large sympathetic oscillations in harbors and on coastal shelves. To minimize this complexity, an attempt was made to restrict wave-observation stations to small islands with steep approaches.

During Operation Ivy, wave stations were occupied at Guam, Wake and Midway. The instruments were located in protected areas, however, and the records, while showing definite arrivals of wave energy, exhibited only a pronounced enhancement of local background, which completely masked the character of the incoming signals.

During Operation Castle, Eniwetok, Guam, Wake, and Johnston were occupied, and although the detecting devices were situated in protected locations, a long hose was led out over the reef into deep water as a sensing syphon. The local background was thus minimized, but the instruments lacked sufficient sensitivity (minimum resolvable wave height: 1 inch) to give optimum results, since the local effects previously observed had given an exaggerated indication of the deep-water wave height from these disturbances. These results have since been re-analyzed and are incorporated in this study.

Previous results have suggested that such long waves might have been produced by the net air-pressure impulse at ranges up to 600 miles from ground zero. This concept was first

reached upon studying the microbarographic records obtained by Projects 1.2a and 17.1 during Castle. Numerical integration of these records to obtain net impulse at the sea surface as a function of range revealed that the sea-surface air-pressure pattern is very complex, but systematic in that the net impulse was greater beyond 200 miles range than at 30 miles.

These results were not considered to be quantitatively significant, because the net integrated impulse is the difference of two already small variables and the response characteristics of the instruments were such as to allow long-duration signals to leak off in an unpredictable manner. In an effort to improve the resolution, microbarographs were borrowed from Sandia Corporation and operated during Operation Redwing at Wake and Johnston islands for all megaton-range tests of the series. Special bleed orifices having calibrated time-constants were installed, and every

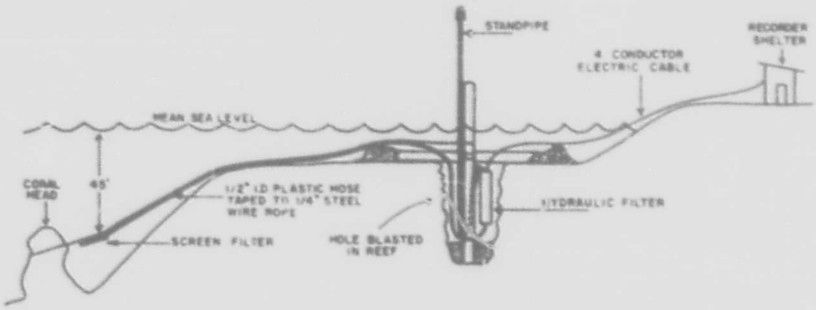

Figure 1 Schematic diagram of typical long-period-wave recorder installation.

effort was taken to minimize recording and reading errors. Despite these precautions, the records have proven to be of little value, since all other evidence indicates that the water waves are locally generated.

INSTRUMENTATION

Long-Period-Wave Recorder. For Operation Redwing, a new long-period-wave recorder was designed ten times as sensitive as those employed for Ivy and Castle and capable of resolving waves less than 1 mm high. These instruments were installed in Sifo (Ailinginae Atoll), Eniwetok, Wake, and Johnston islands. Although originally proposed, Guam was not occupied, since it is part of a large archipelago and the results would not be truly indicative of deep-water conditions.

The long-period-wave recorders used during Redwing were developed and fabricated at the Scripps Institution of Oceanography, as were their predecessors for Ivy and Castle (Reference 1). A schematic drawing of a typical installation is shown in Figure 1. The unit consists of a bandpass hydraulic filter mounted on a vertical standpipe in a protected location and connected hydraulically to the sea by an arbitrary length of standard, $\frac{1}{2}$-inch, plastic garden hose, and to the shore recording station by a four-conductor electric cable.

The hydraulic filter is comprised of two fluid capacities and two capillary restrictions, which limit the flow of fluid into the capacities. The function of the filter is to discriminate against pressure signals, transmitted to it by the hose, which have periodic fluctuations either of higher or lower frequency than that to which the filter is tuned. The frequency-versus-wave-amplitude response of the present filter is shown in Figure 2. A description of an early model recorder and its basic theory of operation are discussed in Reference 2. For Operation Redwing,

the filter was designed to have maximum response to waves having a period of 600 seconds, typical of the waves observed during Castle.

An electric pressure transducer converts the pressure signal within the filter to an electric signal, which is recorded ashore on an Esterline Angus spring-wound strip chart recording milliammeter. The electric signal first passes through a direct-current transistor amplifier, also designed and constructed at Scripps Institution of Oceanography.

The entire system is battery operated, portable, and especially adapted for installation in remote areas, although a regulated power supply is provided for use where 110-volt, alternating-current power is available.

Microbarograph. In addition to wave documentation, microbarograph stations were operated at Wake and Johnston and supplemented by similar observations made by Sandia Corporation

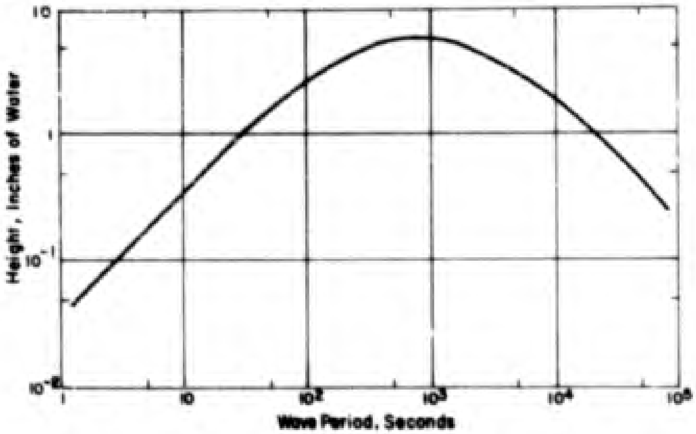

Figure 2 Amplitude response curve for the hydraulic filter. Curve shows output pressure in inches of water as a function of wave period for a 10-inch sine-wave input.

under Project 30.1. These records were to be examined for a clue to the process of generation of long-period waves, since Castle results indicate that these waves are air coupled and independent of source geometry.

The recording microbarographs operated at Wake and Johnston were obtained from the Sandia Corporation and have been previously described (Reference [illegible]).

ISLAND OPERATIONS

As in Operation Castle, the instrument installations at Wake, Johnston, and Eniwetok were carried out by a crew of three men who traveled in rotation to each site and took with them a small boat, diving gear, and necessary special tools and equipment. Upon completion of the three installations, the field crew was split up, with one man returning to each site to act as station operator.

The Ailinginae installation was established by a crew from the Scripps vessel, M/V Horizon. The instrument was designed to be autonomous and was set to run continuously with periodic revisitations by the Horizon for the purpose of changing records.

Prior to making the installations, five men (three operators plus two spares) were put through a three-month period of intensive training which included: (1) qualification course for aqualung

divers (SIO); (2) explosives training in use of shaped charges (ATB, North Island); (3) theory and operation of microbarographs (Sandia Corporation, Albuquerque); (4) operation and maintenance of KLM-7 code decriptor (USACS, Honolulu); (5) installation, operation and maintenance of LP wave recorder (SIO); and (6) operation of Benioff seismometers (SIO)— seismograph stations installed by the USC and GS were also operated on a volunteer basis at Wake and Johnston islands at the request of the Geophysics Branch at ONR.

Upon arrival at each island, the crew selected a station site that was a compromise between favorable exposure to wave signals from Bikini, availability of deep water close to the barrier reef, electric power, and access for easy maintenance. A hole having dimensions at least 3 feet in diameter by 5 feet below sea level was blown in the reef with 40-pound Type M-3, pentolite shaped charges. A 2-inch-diameter galvanized pipe about 10 feet long was then mounted vertically in the hole and secured at the bottom by concrete and at the top by bolting to a heavy scrap-length of structural steel laid horizontally across the hole. The ends of the steel beam were, in turn, secured to the reef by steel spikes and concrete. Next, a $^{5}/_{16}$-inch-diameter galvanized steel cable was strung from the pipe out across the reef, down any convenient reef channel to a depth of about 45 feet into open water beyond the reef, and anchored securely about 4 feet from the bottom with Nicopress clamps. The other end of the cable was led ashore to the vicinity of the recorder shelter, usually constructed specially at each site. The plastic garden hose was then taped at 3-foot intervals to the cable from the pipe out into deep water, where it terminated in a screen to prevent fouling. Finally, the hydraulic filter and standpipe assembly were bolted to the vertical pipe and the electric cable, also taped to the steel cable to prevent chafing on the rocks, was led ashore to the recorder shelter. The shore recorder and the standpipe installation at Wake Island are shown in Figures 3 and 4, respectively.

Approximately 10 days were required to effect each installation, and despite initial complications arising from misshipment of materials, all installations were completed in time for full planned participation in the shots.

CASTLE RESULTS

Tables 1 through 4 give the results of wave measurements made at distant island stations during Operation Castle for shots in the megaton range set off at Bikini Atoll. Since the minimum resolvable wave height was about 1 inch for the early-model recorders used, smaller shots produced no recordable waves at any station.

Long-wave recorders were operated continuously throughout the program except as follows:

Eniwetok Station not in operation until after Bravo (Shot 1).

Guam A deep-water station on the reef one mile north of Ylig Bay failed to indicate resolvable signals for Shots Bravo and Romeo. The station was discontinued thereafter. A second station at the head of Ylig Bay was operated continuously. Although large waves were recorded for all shots, they were not representative of deep-water heights, and are not included in the data. The qualitative results from Yankee (Shot 5) are considered below.

Johnston The installation on the outer reef at Johnston Island was destroyed by storm waves three days prior to Bravo. The station was never restored to operation for lack of spare equipment and personnel.

The Ylig Bay recorder on Guam did not provide representative deep-water wave heights because of the location of the recorder at a point where the wide, shallow bay narrows down to the mouth of the Ylig River, such that local wave heights are very much enhanced over those outside the barrier reef. Additional enhancement occurred when the period of incoming signals coincided with the natural resonant period of the bay. The period of Ylig Bay is almost exactly 9 minutes, as easily determined from normal background when excited by surf breaking across the reef. Such a natural physical system is a sensitive detector of long waves, as shown by Figure 5, which is a plot of relative wave height and period as function of time. The waves observed from Yankee

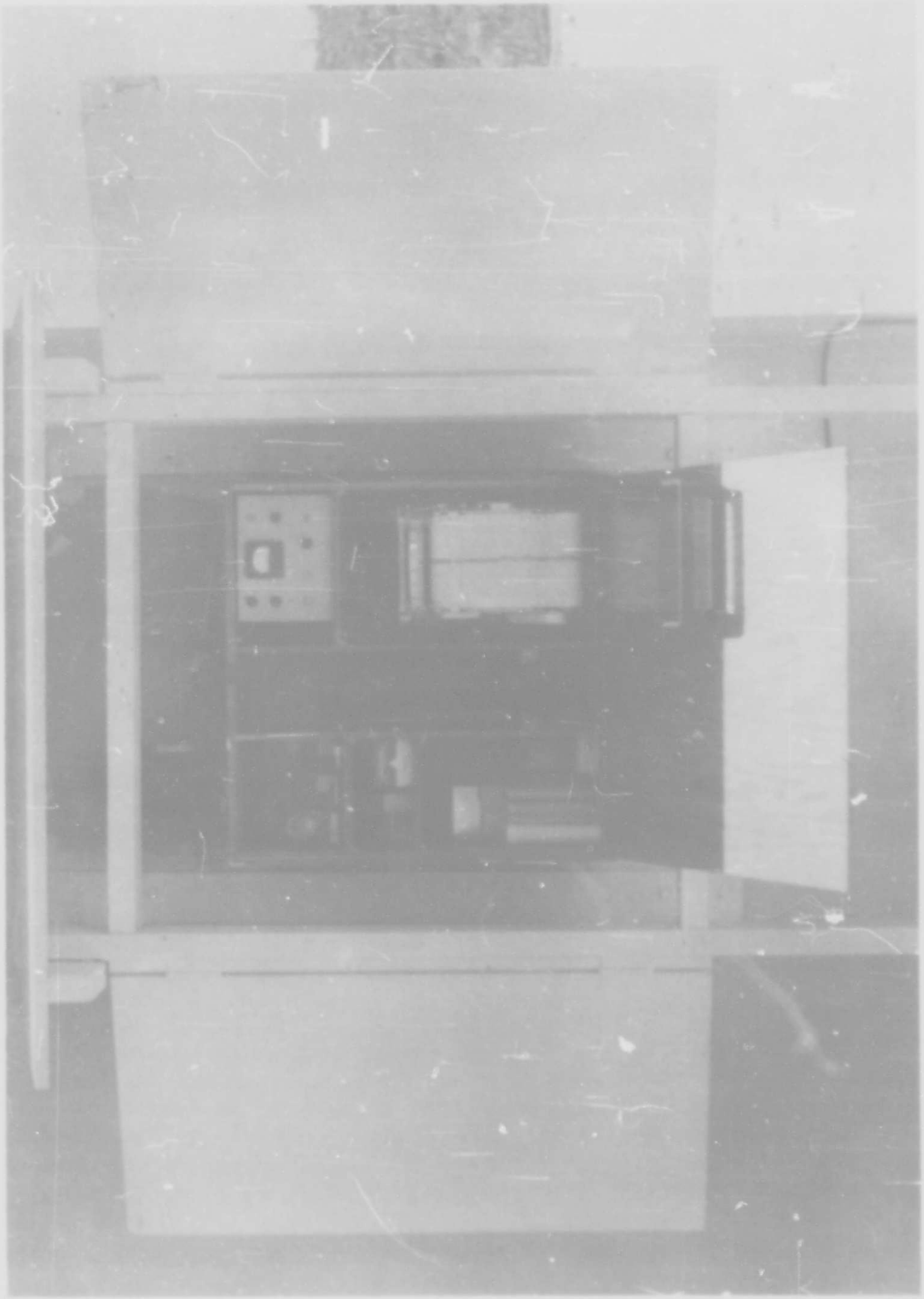

Figure 3 Strip-chart recorder and amplifier installation at Wake Island.

Figure 4 Standpipe and hydraulic filter installation at Wake Island.

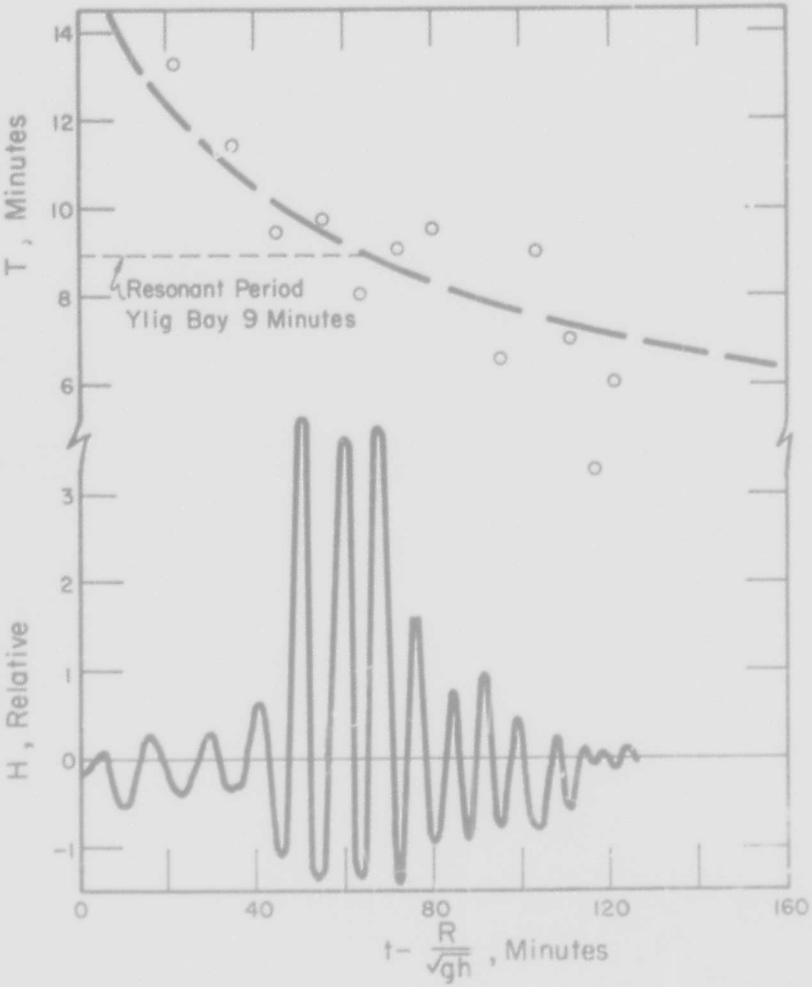

Figure 5 Relative wave height and period as a function of time as observed for Shot Yankee at Ylig Bay, Island of Guam.

TABLE 1 WAVE DATA FOR DISTANT ISLANDS, OPERATION CASTLE, SHOT BRAVO

The following definitions of special abbreviations apply to this table: H, wave height, inches (trough to crest); T, wave period, seconds; $\bar{H}$, RMS wave height of three largest waves; $\bar{T}$, average period of three largest waves; (subscripts refer to three largest consecutive waves in order of occurrence); S/N, ratio of $\bar{H}$ to average background.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Eniwetok	Recorder not operative.								
Wake	2.7	3.6	3.1	3.2	360	390	300	350	3
Guam	Recorder operating but waves too small to be seen.								
Johnston	Installation destroyed by storm waves on February 20.								

TABLE 2 WAVE DATA FOR DISTANT ISLANDS, OPERATION CASTLE, SHOT ROMEO

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Eniwetok	10.1	7.5	4.5	7.7	330	270	366	328	3
Wake	1.9	1.1	2.3	1.8	360	420	270	350	2
Guam	Recorder operating but waves too small to be seen.								

TABLE 3 WAVE DATA FOR DISTANT ISLANDS, OPERATION CASTLE, SHOT UNION

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Eniwetok	5.0	5.0	4.8	5.0	300	330	270	300	2
Wake	1.4	0.8	1.0	1.1	360	300	300	340	1

TABLE 4 WAVE DATA FOR DISTANT ISLANDS, OPERATION CASTLE, SHOT YANKEE

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Eniwetok	12.6	8.1	6.5	10.2	360	450	300	360	5
Wake	3.0	2.6	2.1	2.4	330	450	360	370	4

(Shot 5), clearly indicates both types of enhancement. The early arrivals had a local height of about 8 inches and a period of 13 minutes. The period steadily decreased with time until it coincided with the natural period (9 minutes), at which time the wave height suddenly increased by a factor of seven. As the incident period decreased further, the resonant enhancement ceased and the large oscillations died exponentially. Since the wave height outside the reef was certainly not larger than 2.5 inches at this range, the total enhancement was about 25 to 1. This enhancement probably represents an extreme value, which can be compared to that of 28 to 1 estimated by Shepard (Reference 4) experienced on the Island of Hawaii during the great tsunami of 1 April 1946.

REDWING RESULTS

Observed wave characteristics for stations operated during Redwing are given in Tables 5 through 8. Continuous records were carried on throughout the operation at Johnston, Wake, and Eniwetok,

TABLE 5 WAVE DATA FOR DISTANT ISLANDS, OPERATION REDWING, SHOT CHEROKEE

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Ailinginae	1.3	0.8	0.9	1.0	370	370	420	387	2
Eniwetok	1.8	1.9	1.7	1.8	400	330	270	333	2.5
Wake	Record obtained, but waves obscured by high background.								
Johnston	Record obtained, but waves obscured by high background.								

and a temporary installation was operated at Ailinginae Atoll (Sifo Island) for Shots Cherokee, Navajo, and Zuni. The Ailinginae station was unattended, but was serviced and maintained by personnel based aboard the M/V Horizon. This station was discontinued before Shot Tewa.

Table 9 lists the range and computed arrival time data for the various island stations, and Figure 6 shows the station distribution and travel distance in 20-minute increments for a wave traveling at a speed $C_0 = \sqrt{gh}$ from Bikini Atoll. The average depth $\bar{h}$ used in computing the travel times was obtained from numerical integration of the bottom profiles along great circles connecting the stations according to the relation

$$\frac{1}{\sqrt{\bar{h}}} = \frac{1}{x} \Sigma_{0-i} \frac{x_i}{\sqrt{h_i(x)}}$$

where $h_i(x)$ is the average bottom depth over the horizontal distance increment x_i, and $x = \Sigma x_i$ is the total distance between Bikini and the recording station.

Plots of the wave forms for the various shots at the different stations are shown in Figures 7 through 10, where the times of respective maxima, minima, and zero crossings were lifted from the original records and individual wave amplitudes were corrected according to period for the selective attenuation imposed by the hydraulic filter unit of the recorder. A reproduction of the original chart record for Shot Tewa, as recorded at Eniwetok, is shown in Figure 11. The early part of the record shows the typical background of 10-to-20-second swell superimposed upon 3-to-5-minute surf beat. Shot time is indicated by h + 0 minutes, and the height scale for the shot waves is roughly 1 inch per vertical division. The character of the background is altered significantly in period in the vicinity of h + 17 minutes, which is the expected time of

TABLE 6 WAVE DATA FOR DISTANT ISLANDS, OPERATION REDWING, SHOT ZUNI

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Ailinginae	1.1	4.2	3.0	3.0	320	170	150	213	2.5
Eniwetok	3.5	2.1	1.8	2.6	350	320	310	327	2
Wake	Record obtained, but waves obscured by background.								
Johnston	Record obtained, but waves obscured by background.								

TABLE 7 WAVE DATA FOR DISTANT ISLANDS, OPERATION REDWING, SHOT NAVAJO

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Ailinginae	0.9	1.3	1.2	1.1	240	180	150	190	2
Eniwetok	3.2	3.1	4.3	3.6	350	310	280	313	3
Wake	0.7	0.7	0.7	0.7	390	360	330	360	1
Johnston	0.3	0.5	0.6	0.5	540	480	420	480	1

TABLE 8 WAVE DATA FOR DISTANT ISLANDS, OPERATION REDWING, SHOT TEWA

See Table 1 for special abbreviations.

Station	H_1	H_2	H_3	$\bar{H}$	T_1	T_2	T_3	$\bar{T}$	S/N
Ailinginae	Station discontinued.								
Eniwetok	3.8	3.6	4.0	3.8	360	330	300	330	4
Wake	0.8	1.0	0.8	0.9	450	420	300	390	3
Johnston	0.4	0.6	0.4	0.5	480	480	420	450	1

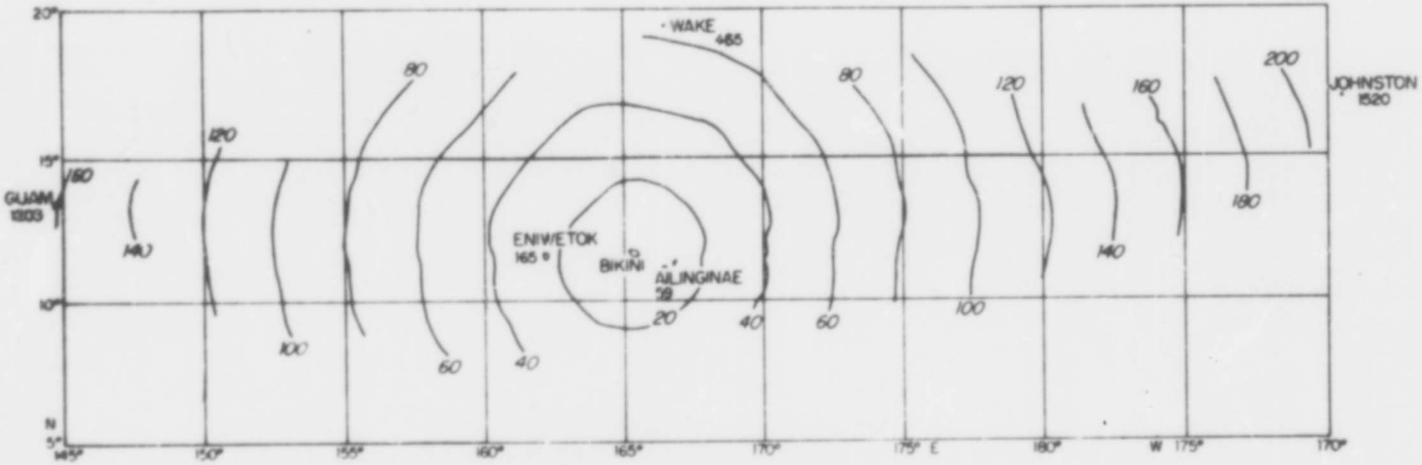

Figure 6 Computed travel distances in 20-minute increments of $\sqrt{gh}$ waves originating at Bikini. Island ranges are given in nautical miles.

TABLE 9 RANGE AND WAVE FRONT TRAVEL TIMES TO DISTANT ISLANDS

Station	Range		Average Depth	Average Velocity $C_0 = \sqrt{gh}$		Travel Time $t_0 = 10^6 R/C_0$	
	$R(ft \times 10^{-6})$	(naut mi)	$h(ft \times 10^{-3})$	ft/sec	m/sec	min	sec
Ailinginae							
a. Zuni	0.36	59	11.6	612	170	9.6	578
b. All others	0.42	70	12.1	623	186	11.2	675
Eniwetok	1.00	165	14.0	670	204	24.9	1,490
Wake	2.83	465	16.1	718	219	65.6	3,940
Guam	7.33	1,203	18.3	767	234	159.0	9,550
Johnston	9.2	1,500	16.0	717	218	213.0	12,700

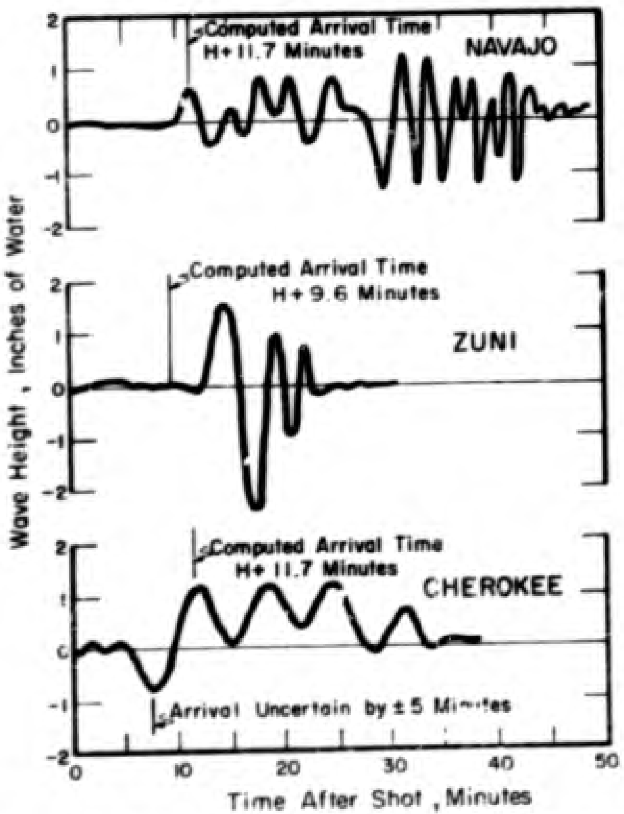

Figure 7 Water waves, corrected for amplitude respo. se, as observed at Ailinginae Atoll.

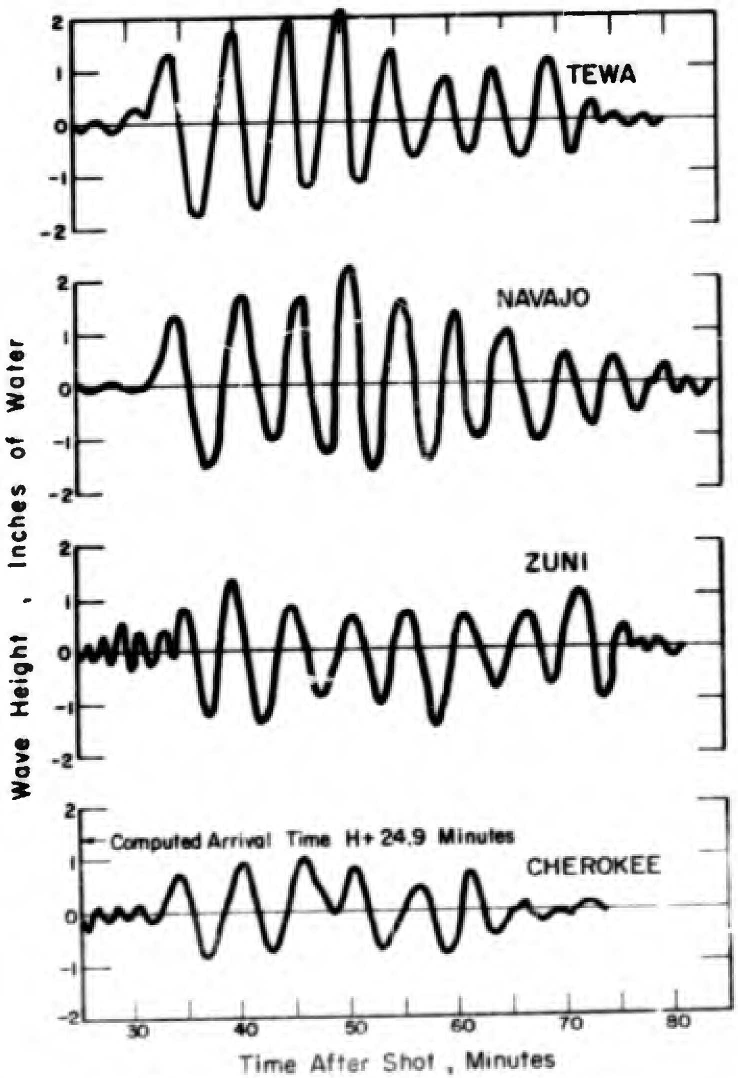

Figure 8 Water waves, corrected for amplitude response, as observed at Eniwetok.

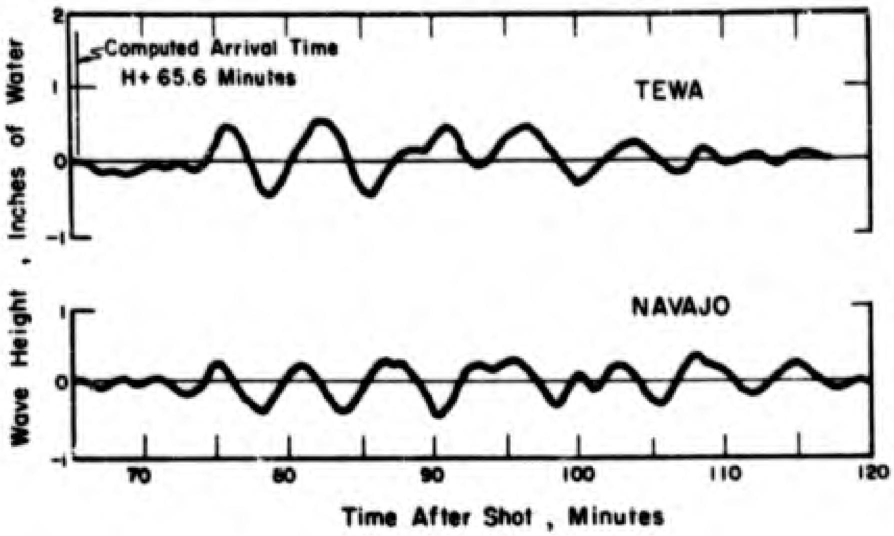

Figure 9 Water waves, corrected for amplitude response, as observed at Wake Island.

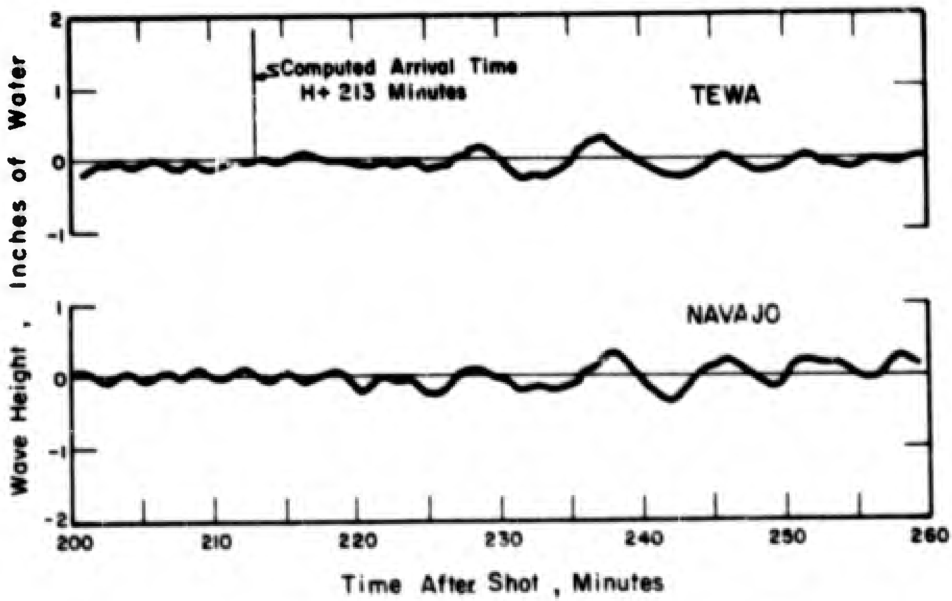

Figure 10 Water waves, corrected for amplitude response, as observed at Johnston Island.

arrival of the air shock wave, but the amplitudes are unresolvable from background. The first large crest arrived at h + 34 minutes, or considerably later than the 25-minute delay based on the velocity $C_0 = \sqrt{gh}$. Such a delay was observed in all records and shows that the first significant crest traveled at less than the theoretical maximum for long waves in water of finite depth, which is characteristic for dispersive wave trains.

Despite the fact that the receiving stations were in different directions, the dispersive character of the waves from the Redwing tests can be obtained by direct comparison of crest arrival data, because the average depth only varied slightly and the travel time varies with the square root of the depth. Figure 12 shows the time of arrival of successive crests as observed at the several stations, where smooth curves have been drawn through the crest points, which are the

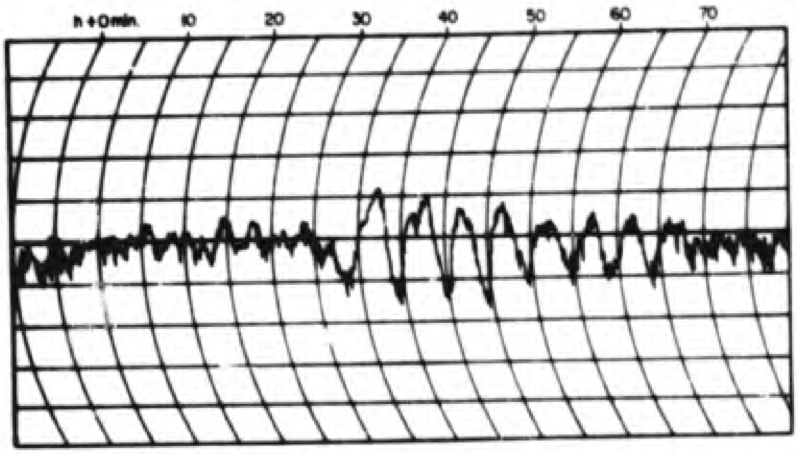

Figure 11 Reproduction of actual record obtained at Eniwetok for Shot Tewa, Operation Redwing. Shot time indicated as h + 0 minutes.

average values from Shots Zuni, Navajo, and Tewa. Although only four crests were clearly observed at Ailinginae and only five at Johnston, and hence the curves are somewhat idealized, the initial dispersion is clearly evident. Beyond Wake Island (465 nautical miles), however, dispersion ceases; and the period and wave length are independent of time. These results, somewhat at variance with commonly accepted theories for long waves, are discussed later in this report.

The variation of maximum wave height with distance is shown in Figure 13, which shows the root-mean-square height $\bar{H}$ of the three highest waves versus range for Shot Tewa. At great distances, where dispersion has ceased, one expects the height to diminish as $1/\sqrt{R}$, and the heights observed at Wake and Johnston have been connected with a line having the appropriate slope ($-\frac{1}{2}$). Within the region of active dispersion, one expects that $\bar{H}$ will diminish approximately as $1/R$, and such a line is drawn through the height observed at Ailinginae.[1] These two

[1]Shot Tewa was not observed at Ailinginae. The reported height was for Zuni, and was corrected for the difference in yield. Although Shot Navajo was observed at Ailinginae, the shot site was on the far side of Bikini and the waves had to travel by a circuitous route around both Bikini and Ailinginae to reach the recorder. Thus the recorded heights were not considered to be as reliable as those from Zuni, which came by a direct route. This situation is shown by the wave forms of Figure 7. The Navajo record is further complicated by the arrival of direct waves at about h + 30 min leaking out of the main pass in Bikini Lagoon.

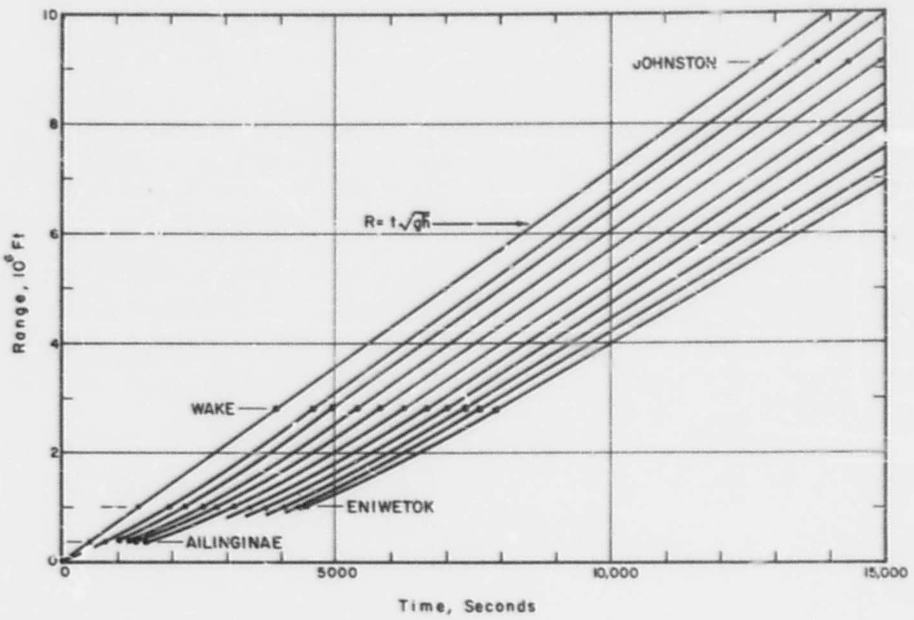

Figure 12 Individual wave crests in space-time, as observed at the island stations. Crest arrival times were averaged for all shots, after correction for site geometry.

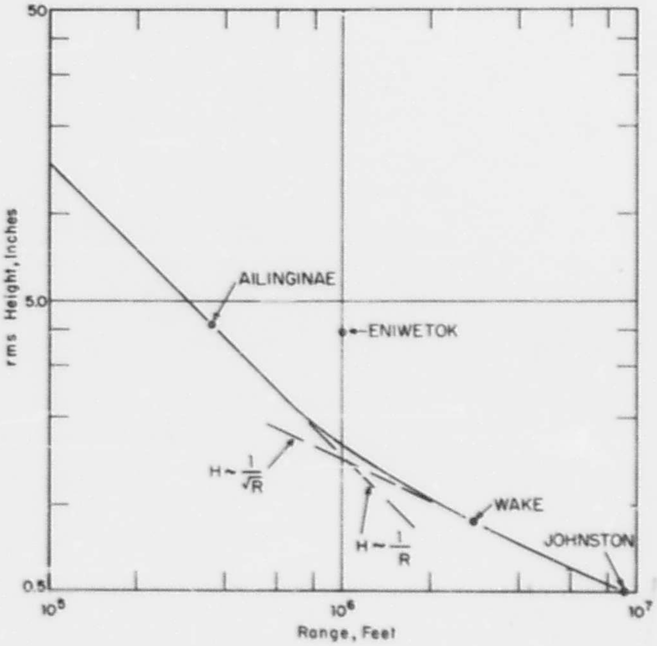

Figure 13 Wave height versus range for Tewa (W = 5 Mt).

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lines have been joined by a smooth curve in the region where dispersion ceases to become important (200 to 500 naut mi). But the height observed at Eniwetok is higher by a factor of 2.4 than that consistent with the other stations, and similar anomalies exist for all other shots observed at Eniwetok. However, Eniwetok is the only observation station having a diameter (22 miles) approaching the deep-water wave length (about 30 miles) of the observed waves. According to Arthur (Reference 5), the above factor is quite consistent with the enhancement to be expected from such waves approaching a circular island at normal incidence.

The observed variation in wave height $\overline{H}$ with weapon yield from shot to shot at the several distant islands is given in Figure 14. The points tend towards alignment in logarithmic coordinates, and the lines drawn through the points for each station have a slope of one, suggesting

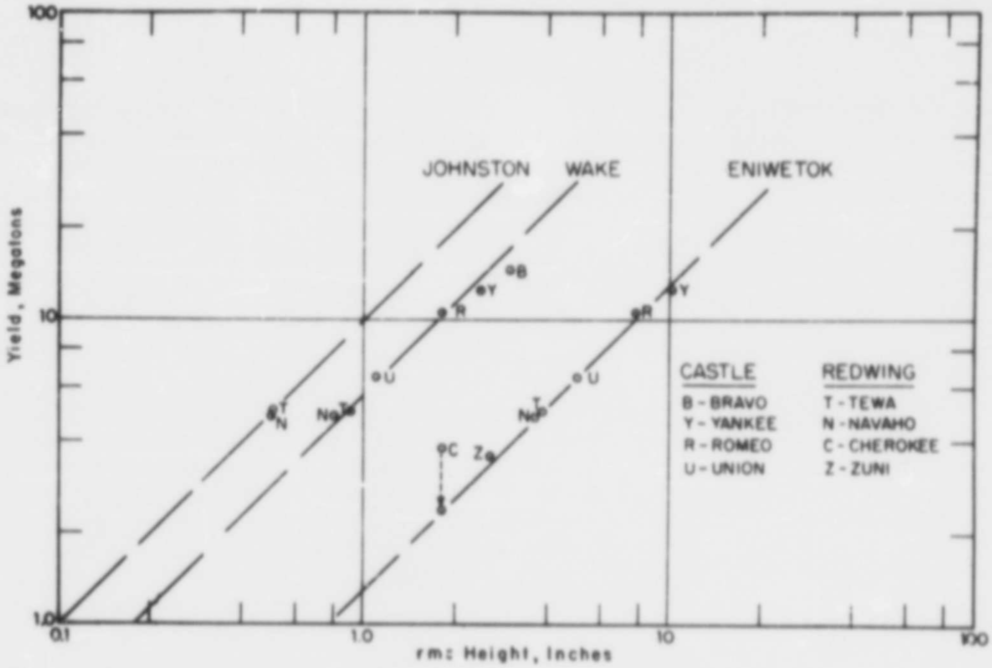

Figure 14 Wave height versus yield. Data for Ailinginae are not included, since they overlap those for Eniwetok.

that the wave height varies directly with the yield, and thus that, since all wave trains were observed to have similar periods, wave energy increases as the square of the yield. This result implies either that larger bombs are more efficient at putting energy into the water, which is unlikely, or that the atoll over which the bomb is detonated is effective in determining what percentage of the total impulse goes into the water.

DISCUSSION

The analysis of the results reported here was carried out as a portion of the work under a 3-year contract for the study of impulsively generated waves (Nonr 233-35) and was distributed as an interim report (Reference 6) under that contract. The conclusions reached in this analysis

are reported below without qualification, and reference is made to the above paper for details and supporting arguments.

Origin of the Waves. The long-period waves observed at the distant island stations are considered to have been generated by the fringe of the air impulse pattern which extended beyond the perimeter of Bikini Atoll. The effective radius of wave generation, R_0', as deduced from an analytic model for the net surface impulse and considerations with regard to the nature of the dispersion and decay of wave height with range, is a function of the yield only, and is given by the relation:

$$R_0' = 2{,}500\,(W/W_0)^{1/3} \text{ feet}$$

where W is weapon yield in kilotons referred to the reference yield W_0 = 0.5 kt. The net impulse is characterized by a central region of high positive impulse surrounded by an annular region of net negative impulse, outside of which the impulse again becomes positive, but at a range where the mean overpressure behind the shock front overpressure has dropped to a very low value. The equation also gives a good approximation to the initial wave length of the sea surface disturbance, which is construed to be a rough image of the net impulse. In all the tests considered here, the high impulse region was over the atoll and less than half of the total impulse was effective in generating waves.

Variation of Wave Height with Yield. In the analytic model, the net impulse increases directly as the range out to the radius of generation, which for the range of yields during Operations Castle and Redwing, is of the same order of magnitude as the mean radius of Bikini Atoll. Thus, the site geometry is important in determining what fraction of the total impulse falls over the sea surface outside the atoll. In the preceding section it was noted that the observed wave height at a given range varied directly as the yield, whereas the dimensions for impulse (length^2 × time) imply that if wave height is proportional to impulse, it should vary as the square root of yield. It is shown in Reference 6 that a unique choice of the generation radius and correction for site geometry results in a predicted variation of effective impulse consistent with the above premise, and that the potential energy represented by the sea-surface disturbance at the radius of generation is in good agreement with that computed from the wave height at the distant island stations.

Character of the Wave Dispersion. Qualitative examination of Figure 12 indicates that the nature of the wave dispersion with time and distance is quite unlike that predicted by Kranzer and Keller (Reference 7), which appears to be the only analytic three-dimensional solution for surface wave generation in water of finite depth. In Kranzer's theory, the wave crests are divided into discrete groups whose position in time and space can be depicted by a series of straight rays converging at the origin of coordinates. The general character of the observed waves is more like that described by Prins (Reference 8), in a series of one-dimensional model studies, in that the initial (and, in the present case, only observable) portion of the wave train consisted of a group of solitary waves of nearly constant period, each of whose velocity increased with distance from the source until it reached the limiting value $C_0 = \sqrt{gh}$. A more-quantitative comparison with Kranzer's theory is given in Figure 15, which is a plot of wave period T versus the parameter $R/\sqrt{gh} \times t$, which essentially defines the position of an individual crest in the wave train for all R and t. According to Kranzer's theory, the period of the first crest is infinite, and those of succeeding crests decrease rapidly near the front and then more slowly towards the rear

of the train. In contrast, the observed variation of period is given by the plotted points, which tend towards alignment suggested by the straight line drawn through the points which can be expressed by the relation:

$$T\ (R/\sqrt{gh} \times t)^{0.8}$$

This result implies that, except for the slight departure from linearity imposed by the deviation of the exponent in the above equation from unity, the entire wave ensemble is essentially similar

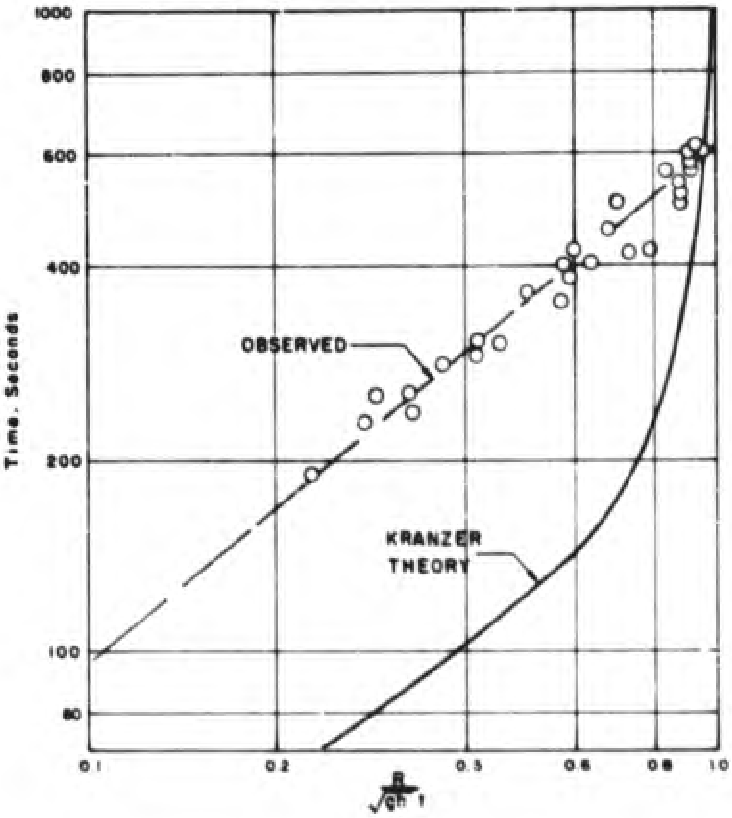

Figure 15 Wave period as a function of the parameter $R/\sqrt{gh} \times t$.

in all observable phases of its development. That considerable departure from the behavior of the waves near the front of the train from that predicted by any linearized theory for sinusoidal waves is to be expected, is proposed by Eckart (Reference 9). He anticipates, rather, that the wave development should conform to the oscillations of the "Airy" function. If Eckart's formulation of the problem has application to the present situation, it can only be at very early times, since the wave train is nearly fully developed at the nearest station (Allinginae), and it still fails to account for the fact that the velocity of individual crests eventually becomes independent of

time and distance. There is clearly a need for reinvestigation of the theoretical aspects of the impulsive production of long waves in finite depth. Such a study is now in progress.

WAVE PREDICTIONS FOR FUTURE TESTS

The fundamental objective in undertaking the wave measurements reported herein was the capability of predicting the characteristics of waves produced by bursts of any yield or source geometry within the confines of an atoll. Although the range of yields covered in the present series (3.8 to 14.5 Mt) is small, it is believed that the information included here, together with the analysis reported in Reference 6, justify extrapolating these results by at least an order of magnitude in yield and to any shot site on an atoll. It was hoped further that derivation of a reasonable model for the net impulse for a surface shot of any yield might permit extrapolation of predictions to include the case of surface shots in deep water. Such extrapolation, however, leads to prediction of wave heights as much as an order of magnitude lower than expected on the basis of scaling up the results of small high-explosive shots to the megaton range. This discrepancy implies that either the mechanism of crater formation is different for high-explosive shots than for nuclear shots — and, hence, they do not scale similarly — or that the relation between impulse and sea-surface deformation is not linear, or both. In the absence of any large-scale surface test in deep water, this uncertainty cannot be resolved.

Surface Shots. On the basis of the analysis reported in Reference 6, the prediction curves of Figure 16 were constructed, giving the root-mean-square wave height H of the three highest waves in a train in deep water expected at the range R from a surface shot of arbitrary yield. Two sets of curves are drawn; both sets originating at the radius of generation given by the equation given in the section, "Origin of the Waves". The dashed curves refer to geometrically similar wave trains, wherein time, water depth, and range are scaled in proportion to the cube root of the yield. These curves were drawn to permit comparison with the results of small high-explosive surface shots, leading to the uncertainty discussed above.

The solid curves refer to waves propagating in water of constant uniform depth of 16,000 feet (the mean depth of the Pacific Ocean), and the same uncertainty applies as for surface shots at scaled depths. However, for surface shots over an atoll, when the curves are entered with the effective yield, as determined by multiplying the actual yield by that fraction of the total impulse which falls over the sea, the curves give accurate predictions for the range of yields of Operations Castle and Redwing. The computation of the effective yield involves a numerical integration of the effective impulse by azimuthal sectors around the shot site according to the procedure outlined in the above reference. In general, the effective impulse increases with yield and proximity to the atoll rim in a nonlinear fashion. The curves predict that a shot having an effective yield as high as 50 Mt could be safely fired at Bikini without producing waves higher than the normal tide range at Eniwetok (3 to 4 feet). This would correspond roughly to an actual yield of 70 Mt at the center of Bikini Lagoon. The primary (lagoon) waves from such a shot, however, would entirely inundate Bikini.

Air versus Surface Bursts. Limited evidence for the wave effects to be expected from air bursts is provided by the measurements made during Shot Cherokee, Operation Redwing, which took place at an altitude of about 4,500 feet over deep water. While quantitative comparison of the observed heights with those from surface shots gives no basis for accurate prediction of the effects of altitude in view of the extrapolation to deep water geometry, the fact that the wave heights from Cherokee were roughly half those from Shot Zuni, a shot of nearly equal yield, de-

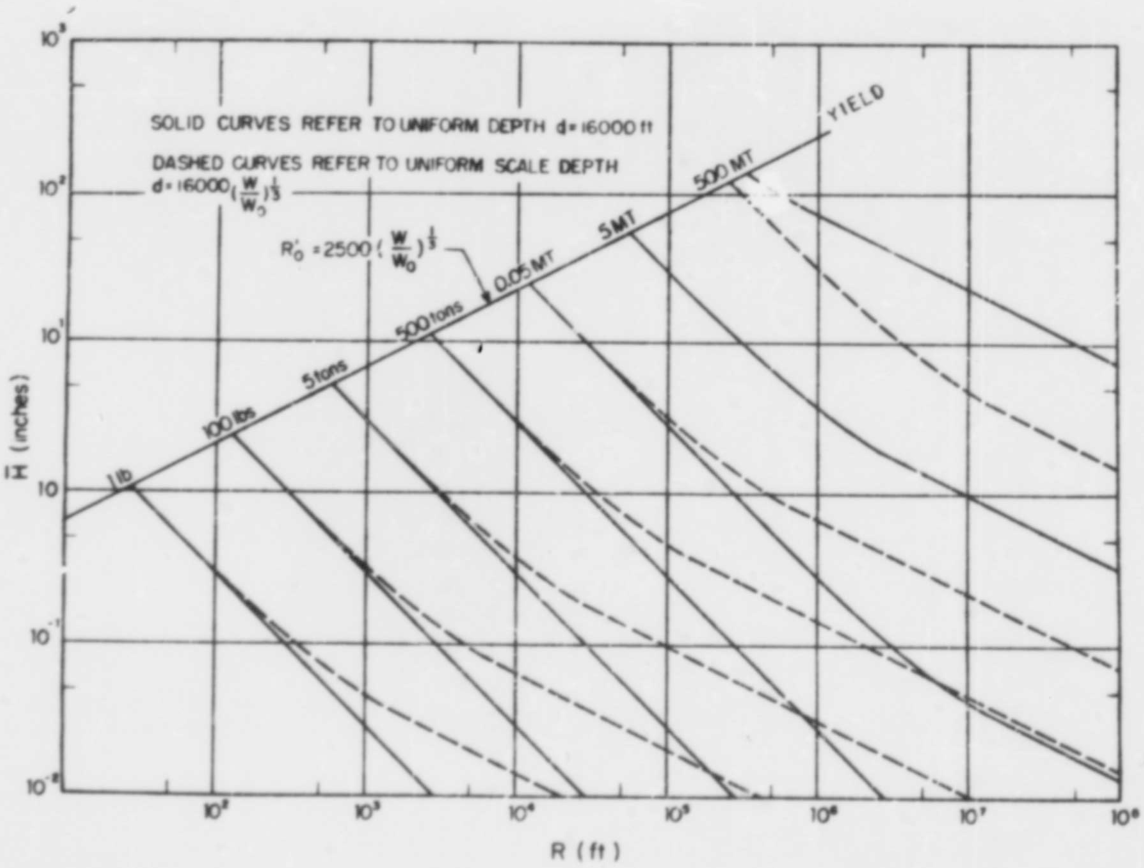

Figure 16 Predicted wave height versus range as a function of effective yield for surface shots over an atoll. Solid curves refer to uniform depth d = 16,000 feet. Dashed curves refer to uniform scale depth $d = 16{,}000\left(\frac{W}{0.5}\right)^{1/3}$ where W is in kt.

spite the absence of atoll shielding, implies that the surface impulse from Cherokee was at least four times smaller than it would have been had the shot occurred at the surface.

SUMMARY

A surface burst in the megaton range set off over an atoll produces a long train of essentially solitary waves, of which the highest crest will be the second or third in the train. The train is fully formed at a distance of about 60 miles and is, in every respect, similar thereafter out to the greatest range of observation (1,500 miles).

The wave train is dispersive out to a range of about 500 miles, the velocity of each crest steadily increasing with time and distance until it asymptotically approaches a limiting value $C = \sqrt{gh}$, after which no further change takes place. The observed dispersion is incompatible with current theory.

The only significant change in wave characteristics with weapon yield is the individual wave height, which was observed to increase directly as the yield at all observation stations. On the presumption that the height should logically increase only as the square root of the yield, the observed variation is considered to be the result of the shadowing effect of the atoll.

The observed decay of wave height with range was consistent from station to station, and in accord with the theoretical premise that the deep-water height should decay as the reciprocal of the range in the region of active dispersion, and as the reciprocal of the square root of range at greater distance. The anomalously high wave heights observed at Eniwetok are construed to be the result of local enhancement.

In a subsequent analysis of the generation mechanism carried out under a separate contract (Reference 6), an analytic model for the net air impulse was computed which adequately predicts the anomalous increase of wave height with yield. The model postulates a finite radius of generation and permits the prediction of waves for surface shots in deep water. Such predictions are substantially lower than those obtained by scaling up the results from small high-explosive tests. This uncertainty cannot be resolved on the basis of present information.

CONCLUSIONS

Analysis of the empirical results of wave measurements at distant island stations has provided a basis for adequately predicting the deep-water height of waves produced by nuclear tests set off over atolls within the range of yields covered by the tests. The present uncertainty regarding the energy efficiency of surface shots does not warrant extrapolation of the present results to the open sea.

The extrapolation to higher yields appears justified in view of the consistency of the results already obtained, at least to 100 Mt at Bikini. However, a 100-Mt surface burst might well produce dangerous waves at ranges of several hundred miles, although a 70-Mt burst at the center of Bikini Lagoon would not endanger shore installations on other islands.

The results from Shot Cherokee indicate that air bursts produce lower waves than surface bursts of equivalent yield, but no quantitative comparison can be made on the basis of the surface impulse model.

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